Analysis of Traffic Flow with Variable Speed Limit on Highway

Hyerim CHO
Ph.D. Student
Dept. of Transportation Engineering
University of Seoul
90, Jeonnong-dong, Dongdaemun-gu, Seoul
130-743 Korea
Fax: +82-2-2210-2653
E-mail: pakacuda@gmail.com

Youngchan KIM
Professor
Dept. of Transportation Engineering
University of Seoul
90, Jeonnong-dong, Dongdaemun-gu, Seoul
130-743 Korea
Fax: +82-2-2210-2653
E-mail: pakacuda@gmail.com

Abstract

Variable speed limit is one of the freeway ITS techniques designed to prevent accidents and traffic slow down by reducing congestion or speed variation between vehicles and lanes prior to arriving at the accident location by limiting speed. This is currently applied and operated on the autobahn in Germany, on M26 in the UK, and in other countries in Europe. Research and development such as effect analysis and operational schemes are actively conducted. In Korea, while people have recognized the need for variable speed limit beginning with Seoul's urban expressway and installed facilities in order to provide guide for speed limit per lane and lane use, there has not been enough development of algorithm for internal administration as well as research on the basic principles behind administering variable speed limit. When looking at the actual status of administration, it is difficult to expect administrative effect of variable speed limit that is faithful to the original purpose, as information on fixed speed is supplied during normal times based on speed limit as criteria and when necessary, an administrator intervenes and manual operation occurs.

The present study provides a mathematical analysis of dynamic traffic flow of basic segment of the freeway during variable speed limit and based on this, offers an implementation model for variable speed limit. For the scope of analysis, a macro approach method centered on aggregated data has been applied after having considered the status on freeway management, and for the traffic flow, the freeway will be given primary attention. This study models and recreates the creation and movement of shock wave diffused downstream from the applicable location if variable speed is applied when capacity disintegration phenomenon such as accident occurs. This study conducts numerical analysis by preparing a scenario in order to verify the form of shock wave that is diffused along the road via variable speed limit by using the developed model.

Ⅰ. Introduction

Variable speed limit forms one of the ITS techniques that is often applied to freeways such as an expressway. The purpose is to prevent accidents and to minimize overall traffic slow down by reducing congestion or speed variation between vehicles and lanes prior to arriving at the

accident location by limiting speed in stages. A separate management technique which has active control concept such as signal control of (interrupted traffic flow)단속류 does not exist in a freeway. The present technique is currently applied and operated on autobahn in Germany, on M26 in the UK, and in other countries in Europe, and related research and development such as effect analysis and operational schemes are actively conducted. Domestically, people have recognized the need for variable speed limit beginning with Seoul's urban expressway and installed facilities in order to provide guide for speed limit per lane and lane use. However, when looking at actual administrative status, one finds that it is not operated according to algorithm for administering variable speed limit but remains at the level of supplying information based on design speed as criteria. Thus, it is difficult to expect effectiveness. Further, there is inadequacy not only with the development of algorithm for administering variable speed limit but also with research on the basic principles behind administering variable speed limit. When looking at the actual administering status, it is difficult to expect administrative effect of variable speed limit that is faithful to the original purpose, as information on fixed speed is supplied during normal times based on speed limit as criteria and when necessary, an administrator intervenes and manual operation occurs.

The present study provides a mathematical analysis of dynamic traffic flow of basic segment of the freeway during variable speed limit and based on this, offers an implementation model for variable speed limit. For the scope of analysis, a macro approach method centered on aggregated data has been applied after having considered the status on freeway management, and for the traffic flow, the freeway will be given primary attention. This study models and recreates the creation and movement of shock wave diffused downstream from the applicable location if variable speed is applied when the phenomenon of capacity disintegration such as accident occurs. This study conducts numerical analysis by preparing a scenario in order to verify the form of shock wave that is diffused along the road via variable speed limit by using the developed model.

Ⅱ. Review of Existing Theory and Related Research

To explain dynamically the change and effect of traffic flow when implementing control on the main-line of the freeway, this study has explored analysis of traffic flow features and research trends for variable speed limit algorithm.

Chris Lee (2004) developed the Real-Time Crash Prediction Model. This model enables VSL control by applying variable speed limit according to the average speed of vehicles in an expressway zone as assumed by the author, and enables speed control in real time by judging crash potential at this time. The significance can be found in that for analysis, microscopic simulation was used and a methodology for securing safety for the speed limit of VSL was combined. The results show that crash potential in sampled expressway zone was less than when there was no control.

P. Allaby (2007) suggested a standard (select from 100km/h, 80km/h, 60km/h) for calculating variable speed limit according to traffic volume, occupancy, and average speed in respect to expressway segment in Canada. The variable speed limit was implemented based on real time (20 seconds as a unit) detector data. The segment surveyed was an area where there is heavy traffic at peak time due to commuting vehicles. The study verified the frequency of expressed speed limit each for peak time and non peak time and analyzed the safety level during variable

speed limit and commuting time change. The results of the analysis show that when variable speed limit is imposed, the relative safety advantage improved by 39% during peak time and decreased by 5% during non peak time. Also, the average commuting time during peak time improved by 11% and by 1.3% during non peak time. This can by analyzed as preventing a driving pattern of stop and go and as maintaining a yet more safe traffic flow, when variable speed limit that approaches the average speed according to traffic condition is implemented.

Zackor (1991) analyzed change in reference to speed distribution between individual vehicles during variable speed limit. It has been confirmed that the overall traffic flow stabilizes when speed is controlled during heavy traffic, because it reduces the speed variation between individual vehicles. By controlling speed, the average speed instead increases, and the capacity is also shown to increase by approximately 5 ~ 10%. This proves that variable speed limit can be an outstanding capacity management technique in a situation that nears the capacity state. Papageorgiou (2007) examined change to traffic volume-density during variable speed limit. According to the results of research, in light of the results of a comparative analysis of traffic volume depending on the existence or non existence of applying variable speed limit, it was noted that critical occupancy increased while the changes in the speed and capacity of individual vehicles is slight when applying the variable speed limit. In other words, it was revealed that the slope difference between traffic volume-occupancy decreases as the speed limit is applied by lowering it.

Lyles (2004) recommended an average speed acquired via the detector and a control index of appropriate speed limit according to occupancy by employing capacity of bottle neck in respect to work zone. As a result of analyzing that effect by applying variable speed limit, Lyles confirmed the effect of increased average speed and reduced average commuting time when variable speed limit is applied. However, because speed is controlled based on an existing and a predetermined index, there is a limitation of not being able to respond dynamically to actual traffic condition.

KANG Gyoungpyo implemented variable speed limit based on real time detector data by setting construction impact segment and speed boundary segment using traffic volume and speed data of work zone and upstream in reference to work zones. KANG conducted simulation for a case where variable speed limit was implemented and a case where it was not implemented by formulating a scenario by differentiating the number of lanes, number of closed lanes, and traffic volume during analysis of the effects of variable speed limit, in terms of the implementation process of variable speed limit per stage. As a result of analysis by applying a level of traffic volume set at 2,500~4,500veh/h during the closing down of lane 1 on a two lane road due to construction work, it has been analyzed that during 3,000~4,000veh/h, there was an effect of increased free traffic flow, increased average commuting speed, and reduced average congestion when compared to a case where variable speed limit was not imposed.

Chris Lee (2007) comparatively analyzed the effect of non control when imposing limit on the moving speed of vehicles via variable speed limit (VSL) while at the same time providing warning message via variable message system (VMS), in respect to a 5 mile segment on an expressway. The method of analysis entails realizing provision of warning message + VSL limit and non limit by using a driver stimulator and examining the results of such a realization via a statistical approach using binary logit model. The results of analysis reveal that generally, vehicles in the segment in question moved at uniform speed. And as a result of expressing the analysis results in a speed-distance graph, the result of employing provision of warning information and VSL reveals that the speed when compared to non limit was shown as

comparatively uniform. Especially, it has been analyzed that the phenomenon of sudden drop in speed due to unanticipated situation has not transpired.

Papageorgiou (2007) examined change in traffic volume-density during variable speed limit. According to the results of research, in light of the results of a comparative analysis of traffic volume depending on the presence or absence of applying variable speed limit, while the changes in the speed and capacity of individual vehicles is slight when applying the variable speed limit, it was noted that critical occupancy increased. In other words, it was revealed that the slope difference between traffic volume-occupancy decreases as the speed limit is applied by lowering it.

When looking at related research conducted domestically, PARK Jieun (2009) analyzed the operational effect of variable speed limit when capacity is reduced by 50% due to accident and explained it using traffic flow model and shock wave theory. According to the results of research, when imposing a variable speed limit of 60km/h in an environment of 100km/h, it was confirmed that there was an effect of delaying the creation of a queue because vehicles reduce their speed in advance prior to arriving at the accident location. Also, the research conducted a theoretical inspection of the effects of variable speed by verifying the pattern of shock wave created when variable speed limit is applied and expressing it as q-k curve.

Ⅲ. Basic Assumption

In order to facilitate the analysis of the features of traffic flow and the development of a model in reference to variable speed limit on freeway, this study has set the following two basic assumptions. First, applying the concept as suggested by Michalopoulos, this study has expressed as Characteristics the boundary where changes in speed, density, and traffic flow which differ from one another because the features of traffic flow varies. The Characteristics which could form via variable speed limit have been classified and suggested as Initial condition, Control Strategy, and Shock wave. Among these, the Shock wave appears on the boundary surface of two differing traffic flows when features of traffic flow change via Initial condition and speed limit, or a new Shock wave appears when more than two shock waves intersect. In the present analysis, when implementing variable speed limit according to the occurrence of an event or unanticipated situation in respect to the freeway main-line, because this serves as an important factor that determines the presence or absence of speed limit and the type of shock wave which has the possibility of occurrence of change to limit capacity, it is prescribed as Characteristics.

This study has examined the capacity and critical density at the time of applying a speed limit based on analysis conditions as criteria prior to implementing an analysis according to variable speed limit. The speed limit to be applied in the present analysis was set via a gradation of 20km/h until 100, 80, 60, and 40km/h in order to understand various traffic flow conditions. According to the results of analysis, when the speed was changed from 100km/h to 60km/h, in terms of the variation of traffic volume and density, capacity variation was slight as can be seen in the results of Papageorgiou (2008)'s research from among existing research. However, critical occupancy was found to increase as the speed limit was lowered. This shows that by implementing VSL, capacity decrease almost never occurs if the speed limit is changed. Except when the speed is lowered down to 40km/h, it has been found that capacity likewise decreases. Thus, we know that when applying VSL, one must consider an appropriate speed for

maintaining capacity. Based on the deduced results of <Figure 1>, the capacity per speed limit and the density critical value for analysis of variable speed limit is set and applied as <Table 1>.

VI. Analysis of Traffic Flow Features During Variable Speed Limit

In order to explore changes to traffic features when adjusting the speed limit for the basic segment of an expressway, this study has looked at the change to q-k curve at this time as well as at the configuration of working drawing. In terms of variable speed limit, this study has examined the form of the Characteristics from the trajectory of working drawing and vehicle when 1 time speed limit is implemented from basic speed limit of $u_1$to $u_2$concerning the xmsegment. <Figure 2> shows the working drawing based on vehicle trajectory as standard when changing the speed to $u_2$by applying variable speed from the standard speed limit of $u_1$in reference to a specified segment and when limiting again to u_1, which is the basic speed limit after operating a variable speed of $u_2$for a certain amount of time.

Here, if the density (k) and traffic volume (q) are represented as d; distance headway and h; time headway, the features of traffic flow changes and as a result differing changes to speed, density, and traffic volume transpires, which is known as boundary line. This is also called, Characteristics, and all together, 6 could be observed. Relevant details are as <Figure 3>.

Case ① is applicable when implementing speed limit from $u_1 \rightarrow u_2$ based on $t$point in time on the working drawing. As a result of exploring the features of traffic volume change based on the Characteristics between sphere A-B as standard, while the distance headway did not change, the time headway was seen to increase. When expressing this as traffic volume and density on the q-k curve, a pattern emerges where the density does not change and the traffic volume decreases.

Case ② is applicable when implementing a speed limit from $u_1 \rightarrow u_2$ at x where variable speed limit is enforced. As a result of exploring features of traffic volume change based on the Characteristics between sphere A-C as standard, while the time headway did not change, the distance headway was shown to have decreased. When representing this as traffic volume and density on the q-k curve, a pattern emerges where the traffic volume does not change and the density increases.

Case ③ entails a situation where $u_2$speed limit is implemented at location $x$and at $t$point in time, and shock wave occurs between B-C due to 2 Characteristics which implements speed limit. As a result of exploring the features of traffic volume change based on B-C Characteristics as standard, while the speed limit for two spheres was u_2, both the time headway and distance headway were shown to have changed.

Case ④ entails a situation where a speed limit of $u_2 \rightarrow u_1$ at location $x$is revoked. As a result of exploring features of traffic volume change based on the Characteristics between sphere C-A as standard, while the time headways did not change, the distance headway was shown to have increased. If this is represented as traffic volume and density on q-k curve, a pattern appears where the traffic volume does not change and the density decreases.

Case ⑤ entails a situation where speed limit of $u_2 \rightarrow u_1$ at t' point in time is revoked. As a result of exploring the features of traffic volume change based on the Characteristics between sphere C-D, while the distance headway did not change, it was shown that the time headway decreased. When representing this as traffic volume and density on q-k curve, a pattern appears where the density does not change but the traffic volume increases.

Case ⑥ entails a situation where a full recovery to a speed of u_1, which is the initial state, with t' point in time and location x as standard, and likewise, shock wave occurs between D-A due to two Characteristics which revoke the speed limit. As a result of exploring the features of traffic volume change with the Characteristics between D-A as standard, while the speed limit for the two spheres was u_1, it was shown that the time headway and distance headway both increased. What this means is that the traffic volume and density are shown to increase in a speed of $u_1$if expressed on a q-k curve.

If the change to traffic flow after implementing variable speed limit is organized in a relational expression of q-k based on the above results, it can be represented as follows. When the speed changes to u_2 by applying variable speed, the traffic flow changes from location A to location B. At this time, the rate of traffic flow decreases from q_a to q_b because the speed decreases even though the density for both A and B are identical at k_b. The features of traffic flow rises along the $u_2$curve because the traffic flow transpires with the changed speed as standard. If the speed at location C is restored again to u_1 from u_2, the features of traffic flow changes to location D on $u_1$from location C. Here likewise, while the density remains the same at k_c, the rate of traffic flow increases from $q_c$to $q_d$due to an increase in speed. Afterwards, it is restored to location A, which is a state of traffic flow prior to applying variable speed.

If variable speed is applied in a situation where capacity has decreased due to an accident, six Characteristics of Picture 3 are expressed. And when lowering of capacity occurs due to an accident, a shock wave is newly created if it intersects due to the Characteristics and lowering of capacity which appears when the variable speed proposed earlier is applied.

Ⅴ. Development of a Model for Variable Speed Limit

To develop a model for variable speed limit, traffic flow change which could occur when implementing variable speed limit was modularized based on the pattern suggested earlier and was defined as follows.

When observing without making change to the speed from existing speed of $u_1$for a specified segment, the traffic flow condition shows either an increase (Point A) or a decrease (Point B) in terms of traffic volume and density. If the speed is limited to $u_2$by applying variable speed, a phenomenon arises where density is maintained and traffic volume decreases (Point C) as shown in the above picture. Conversely, if speed limit is upwardly adjusted (Point D), the density again does not change and the traffic volume increases.<Figure 4>

The determinative factor for the second shock wave was suggested as change of control capacity. Generally, in terms of capacity decrease due to occurrence of an event, the capacity restoration time differs according to how quickly implementation of traffic management is processed. In such an environment, in order to determine speed limit dynamically or to set the

scope of limit, there is a need to calculate the shock wave by verifying in real time how disintegrated capacity changes. The present study can consider how the change to limit capacity increases or decreases as focused on an arbitrary point E, when capacity on q-k curve disintegrates with G point as a reference point.

When considering that traffic flow features change until case 1 ~ 4 according to variable speed limit strategy and that limit capacity changes dynamically according to the degree of occurrence of an event, if one were to suggest a shock wave pattern which may occur via variable speed limit, it can be organized in a way that shows the appearance of the following 10 types of shock waves. <Table 2><Figure 6>

This study considers the shock wave speed as u_t, queue position as X, and unit time as $\Delta t$and calculates the location of the shock wave by judging the existence or non existence of occurrence of shock wave per unit distance. First, in the case where capacity decreases due to such factors as an accident without control conditions, the speed of shock wave occurrence and location per unit time transpires as follows.

$$u_w = \frac{q_a - q_b}{k_a - k_b} \cdots\cdots ①$$

$$X = u_w \cdot \Delta t = \frac{q_d - q_a}{k_d - k_a} \cdot \Delta t \cdots\cdots ②$$

where u_w: Shock Wave Speed

q_a: Upstream Traffic Volume q_b: Downstream Traffic Volume

k_a: Upstream Traffic Density k_b: Downstream Traffic Density

X: Shock Wave Location Δt: Unit Time

If the relational expression of traffic volume-density is suggested as ③ with the implementation of variable speed limit, the process of calculating traffic volume, density, and speed as well as the speed and location of occurrence of shock wave is suggested as follows.

$$\begin{cases} q = u_f \cdot k & ,(k < k_c) \\ q = u_b \cdot (k_1 - k) & ,(k_c \le k \le k_1) \end{cases} \cdots\cdots ③$$

Where u_f: Free Speed (Limit Speed)

q_i: Rate of Incoming Traffic Flow q_c: Rate of Maximum Traffic Flow (Capacity)

k_l: Critical Density k_c: Congestion Density

When the volume of inflow traffic moving at the speed of $u_f$is considered to be $q_i$and the density to be $k < k_c$, the traffic volume and speed are calculated as follows.

$$q_d = u_f \cdot k, \quad k = \frac{q_d}{u_f} \quad \cdots\cdots ④$$

If the traffic volume and speed of the location where capacity is reduced is calculated, it is as follows. α which is the rate of capacity reduction was substituted in order to facilitate calculation, and it is suggested in a way that makes possible dynamic fluctuation after considering a pattern of collected data.

$$q = w_e \cdot (k_1 - k), \quad q = \alpha q_c \alpha q_c = w_e \cdot (k_1 - k)^{k = k_j - \frac{q_c}{w_e} \cdot \alpha} \quad \cdots\cdots ⑤$$

Traffic Volume : $q = \alpha q_c$, α = Rate of Capacity Reduction

Density : $k_c \leq k \leq k_1$

Based on the calculated traffic volume, density, and control speed as standard, the speed and location formula have been deduced. The result is formulas ⑥ and ⑦.

$$u_w = \frac{q_A - q_B}{k_A - k_B} = \frac{q_A - \alpha \cdot q_c}{\frac{q_d}{u_f} - \alpha \cdot \frac{k_j \cdot q_c}{w_e}} \quad \cdots\cdots ⑥$$

$$X = u_w \cdot \Delta t = \frac{q_A - \alpha \cdot q_c}{\frac{q_d}{u_f} - \alpha \cdot \frac{k_j \cdot q_c}{w_e}} \cdot \Delta t \quad \cdots\cdots ⑦$$

One can recognize the location of shock wave per unit time and segment by dynamically applying the data on traffic volume and speed that are collected from the inspection information per situation, according to the speed limit strategy based on formula ⑦ as standard.

Ⅵ. Implementation of Numerical Verification

In order to verify the pattern of expansion of shock wave along the road via variable speed limit using a developed model, this study explains the model based on numerical analysis. For an assessment of the applicability of the model, the structural conditions and traffic features of the location to be analyzed are set as follows.

•Structural Features of the Road

- A total of 12.0km of expressway segment
- Number of Lanes: 2 lanes in either direction
- Main-line basic segment that excludes the entrance/exit segment

•Traffic Features

- Analysis of passenger vehicle standard
- Capacity: 1,800 vehicles/time/lane
- Inflow Traffic Volume: 1,500 vehicles/time/lane
- Basic speed limit: 120km/h

•Facility Installation Standard

- Installation of 0.5km interval detector (Δd)
- Installation of 1km interval VSL
- Rate of observance of speed on the part of the driver 100%
- Analysis time interval: 60 seconds (Δt)

In order to enable planning of variable speed limit based on the already suggested assumption and relational formula as standard, the following scenario has been prepared, and based on this as standard, a numerical analysis was conducted.

·Observance of a speed of 120km/h
·Blockage of lane 1 due to an accident (α =0.5)
·Commencement of variable speed limit 5 minutes after an accident
① A 10 minute limit at 100km/h of the upstream ($-\Delta u$ =-20km/h) (6 VSL limit)
② Afterwards, a 10 minute limit at 80km/h ($-\Delta u$ =-20km/h) (6 VSL limit)
·Resolve accident 25 minutes after an accident
① Afterwards, remove speed limit at 120km/h ($+\Delta u$ =40km/h)
·Total limit time: 20 minutes

As a result of analysis, the traffic flow, which maintained a speed of 120km/h, showed a reduction of capacity from 3,680 vehicles/hour to 1,840 vehicles/hour 10 minutes after commencing analysis due to an accident. Because of the accident, a shock wave to upstream occurred at 7.25km/h and after 5 minutes, the speed of the shock wave was reduced to -4.125 from the 2nd VSL of the upstream as a result of limiting six. Maintaining a speed of 100m/h for 10 minutes, the shock wave again increased to -7.48km/h as traffic volume increased. Subsequently, as a resulting of imposing limit for 10 minutes at 80km/h, it was analyzed that the shock wave decreased to -3.61km/h. 25 minutes after an accident, as it is taken care of, the capacity was restored to a normal figure. Accordingly, restoration was made to a capacity condition where the shock wave's speed is 11.87km/h.

When examining change in terms of traffic volume and density due to change to traffic situation, if limiting speed to 100km/h from 120km/h after an accident, the density is maintained at 25 vehicles/km and the traffic volume decreased to 3,000 vehicles/hour to 2,500 vehicles/hour.

After 10 minutes, if the speed is again limited to 80km/h from 100km/h, a phenomenon emerged where the density is maintained at 30 vehicles/km and the traffic volume decreases to 2,400 vehicles/h. This is the same phenomenon as that which can be seen in the result of inspecting the speed of the shock wave and density variation which emerge when calculation is made numerically.

Ⅶ. Conclusion

In the present research, the main theme had to do with the replication of the form of actual occurrence of shock wave by theoretically verifying and modeling the traffic flow phenomenon which appears when variable speed limit is applied. In respect to the situation where speed limit is changed according to the occurrence of accidents, this study recognized the transition phenomenon of traffic flow and the continuous transition state of traffic flow by using a relational diagram of traffic flow-density and shock wave theory.

Also, as a result of expressing working drawing based on archival data acquired from simulation and of making theoretical verification using traffic flow model (traffic volume-density model) and shock wave theory, it has been analyzed that all the speeds of the shock wave were similar to each other. Especially, this study likewise was able to prove the verification of the case where speed is variably applied for a specified length of time by confirming and verifying the transitional state of traffic flow caused by changes to the speed limit. At present, research continues to be carried out in order to complete in the future an assessment of applicability by additionally configuring a scenario that has yet greater probability to occur and to realize a micro-simulator via PARAMICS API. When this is completed, it is anticipated that we can develop numerous variable speed limit models and operational programs based on the results of theoretical verification and simulation of the present research.

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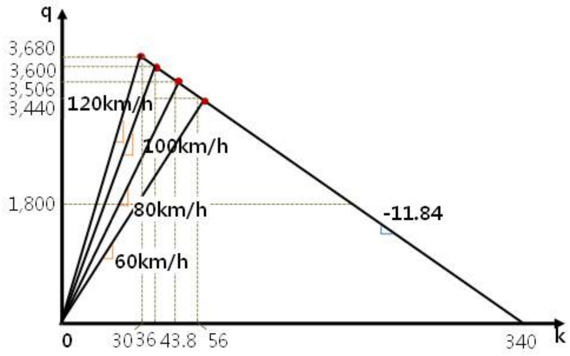
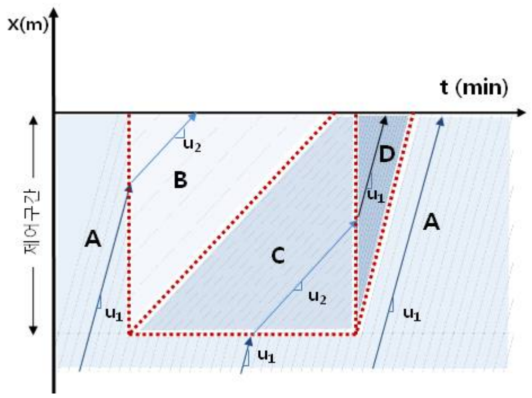
<Table 1> Capacity, Critical Density

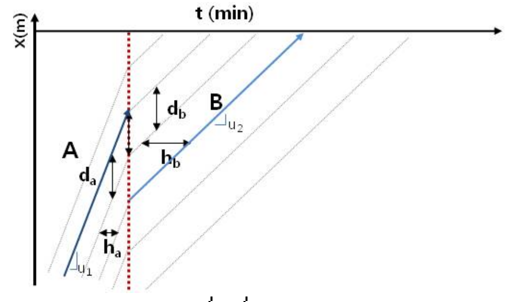
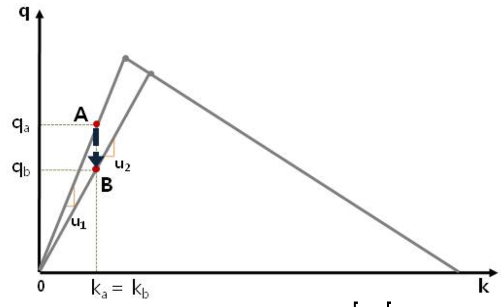
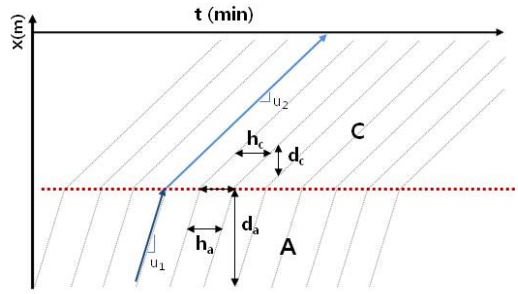
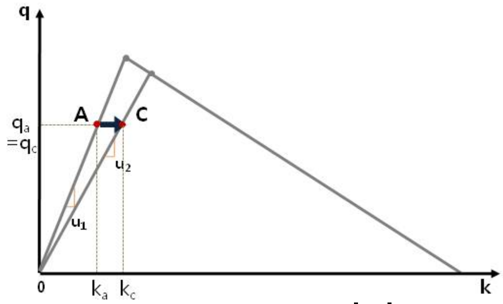
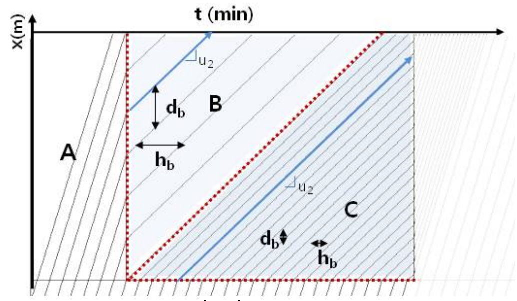
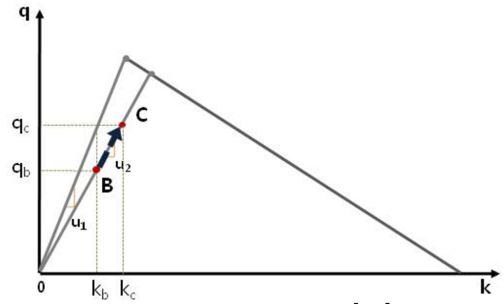
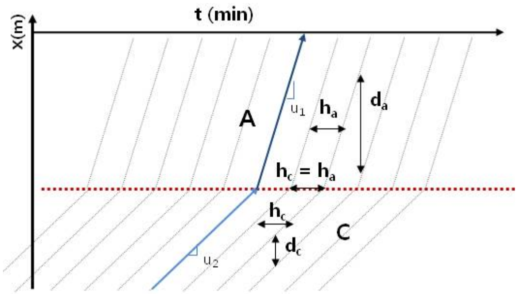
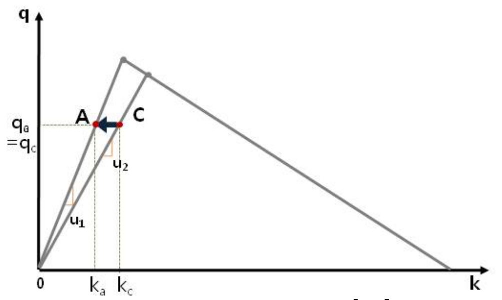
Speed limit	Capacity (veh/h/l)	Critical density (Veh/km/l)
120km/h	1,840	15.3
100km/h	1,800	18.0
80km/h	1,753	21.9
60km/h	1,720	28.6
40km/h	1,560	39.0



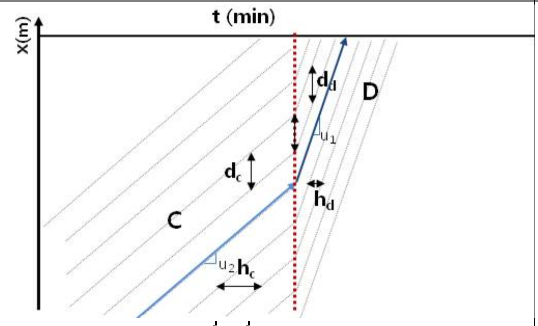
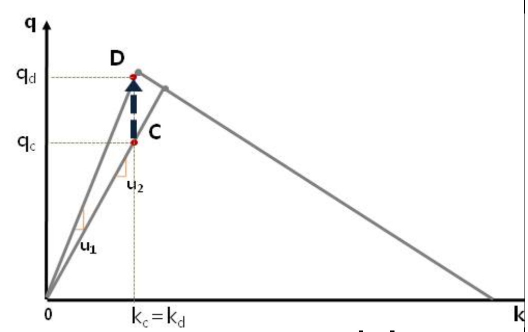
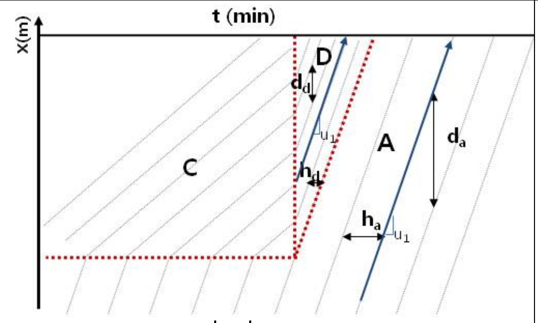
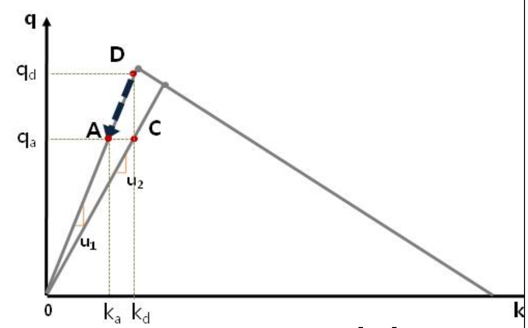
<Figure 1> Change of fundamental diagram due to speed limit



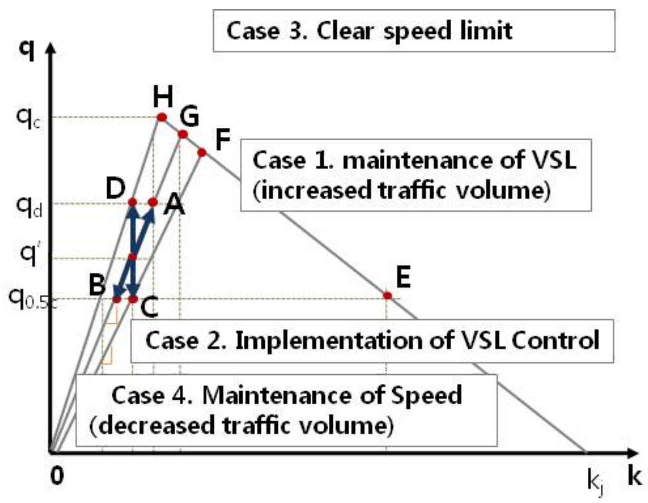
<Figure 2> Shockwave

	<Vehicle trajectory based on time-distance diagram>	<flow-density(q-k) diagram>
case ① reducing speed limit $u_1>u_2$	 time-headway : $h_a<h_b$, distance-headway : $d_a=d_b$	 flow : $q_a>q_b$, density : $k_a=k_b$
case ② reducing speed limit 속도감소 : $u_1>u_2$	 time-headway : $h_a=h_c$, distance-headway : $d_a>d_c$	 flow : $q_a=q_c$, density : $k_a<k_c$
case ③ u_2	 time-headway : $h_b>h_c$, , distance-headway : $d_b>d_c$	 flow : $q_b<q_c$, density : $k_b<k_c$
case ④ Increasing speed limit : $u_2<u_1$	 time-headway : $h_c=h_a$, distance-headway : $d_c<d_a$	 flow : $q_c=q_a$, density : $k_c>k_a$

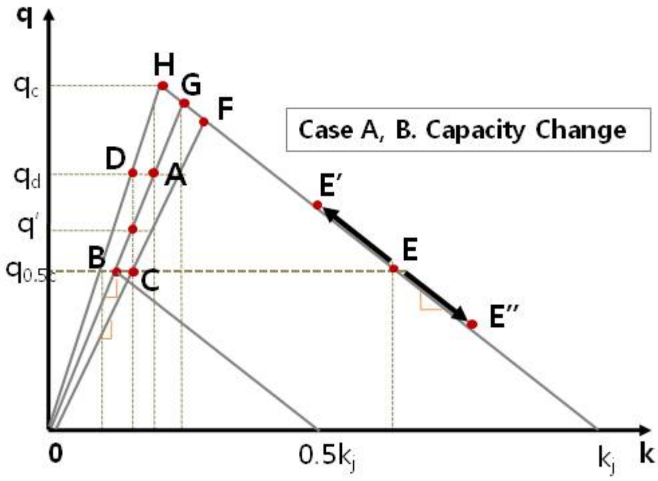
<Figure 3> changes of shockwave and flow due to VSL

	<Vehicle trajectory based on time-distance diagram>	<flow-density(q-k) diagram>
case ⑤ Increasing speed limit : $u_2 < u_1$	 time-headway : $h_c > h_d$, distance-headway : $d_c = d_d$	 flow : $q_c < q_d$, density : $k_c = k_d$
case ⑥ u_1	 time-headway : $h_d < h_a$, distance-headway : $d_d < d_a$	 flow : $q_d > q_a$, density : $k_d > k_a$

<Figure 3> changes of shockwave and flow due to VSL(continued)



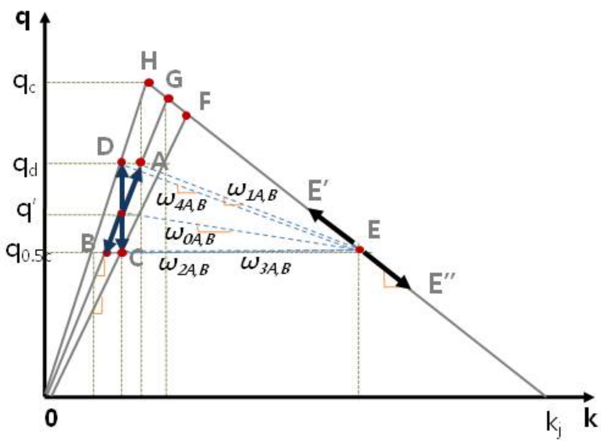
<Figure 4> Control Strategy of VSL



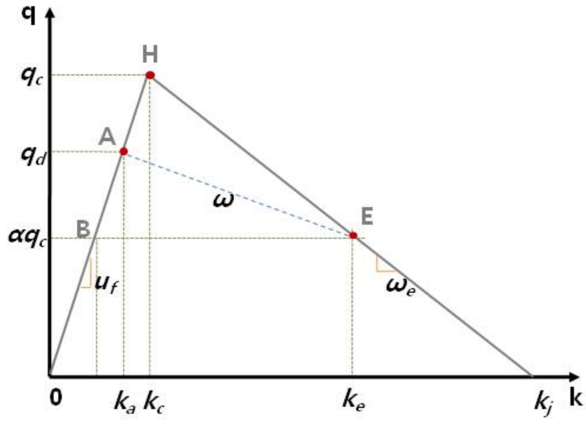
<Figure 5> Shockwave due to change to critical point of capacity

<Table 2> Shock Wave Patterns

Classification	Increase in Bottle Neck Capacity	Decrease in Bottle Neck Capacity
Case 0. No Fluctuation	$\omega_{0,A}$	$\omega_{0,B}$
Case 1. Increase in Traffic Volume	$\omega_{1,A}$	$\omega_{1,B}$
Case 2. Decrease in Traffic Volume	$\omega_{2,A}$	$\omega_{2,B}$
Case 3. Decrease in Speed Limit	$\omega_{3,A}$	$\omega_{3,B}$
Case 4. Increase in Speed Limit	$\omega_{4,A}$	$\omega_{4,B}$



<Figure 6> Result of Analysis of Shock Wave Pattern



<Figure 7> Relational Formula of Traffic Volume-Density